Effect of Broadband Nature of Marine Mammal Echolocation Clicks on Click-Based Population Density Estimates

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LONG-TERM GOALS

The long-term aim of the project is to support passive acoustic monitoring of Odontocetes by improving the modeling of detection functions for broadband echolocation clicks used to estimate animal abudance.

OBJECTIVES

This project aims to demonstrate how the detection process of broadband clicks can be modeled for different marine mammal species and detectors and assess the magnitude of error on the estimated density due to various commonly used simplifying assumptions in the modeling process. Our main purposes are to quantify potential biases in the population density estimate for selected species and detectors caused by narrowband assumptions made in the passive sonar equation when modeling detectability of broadband clicks, and to understand the factors affecting the magnitude of this bias to enable extrapolation to other species and detectors.

APPROACH

Key individuals at University of St Andrews: Thomas (CREEM), Tyack (SMRU)
Key individuals at TNO: Ainslie, von Benda-Beckmann

Technical approach:
This project is in collaboration between TNO (PI: Michael Ainslie, grant number : N000141410409) with the University of St. Andrews (grant number: N000141410396, PI: Len Thomas).

The detectability of broadband echolocation clicks was estimated by using two approaches: 1) by simulating echolocation clicks in real noise and empirically measure the effective detection range and areas by applying different detectors to the modeled data. 2) by simulating the effective detection range and area by the use of the passive sonar equation.

Synthetic acoustic data was created by propagating a recorded echolocaton click $f_S(t;r)$, and adding this to real recorded background noise $f_N(t)$, $f_{S+N}(t; r) = f_S(t;r) + f_N(t)$ (as illustrated in Figure 1). As a basis for the source echolocation clicks recordings of on-axis echolocation clicks were used. These recorded source clicks were used to model the corresponding echolocation clicks at the different ranges of interest, accounting for the effects of frequency dependent propagation losses absorption on both propagation loss and detector performance.

The magnitude of the relative bias caused by applying the narrowband assumption was estimated by comparing the effective detection area for a broadband echolocation click modeled using a broadband (BB) approximation of the propagation loss, to the effective detecton area modeled using a narrowband (NB) approximation for the propagation loss (Figure 2).

To estimate the detection probability the resulting modeled received signal plus noise were then fed through two detectors: 1) a sub-band energy detector; 2) a power-law Page test detector (van IJsselmuide and Beerens, 2004),. The detection probability was established by repeating the process for multiple realizations of the noise.
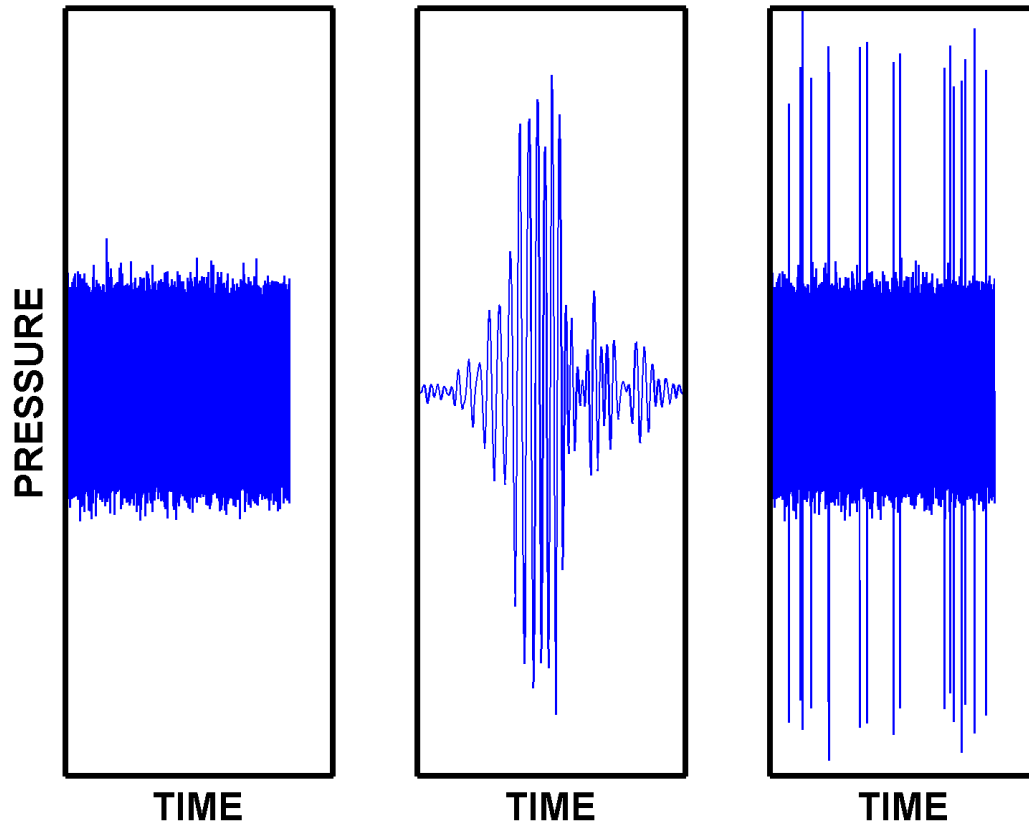
Figure 1 : Illustration of modeling procedure for generating test data for . Simulated echolocation clicks are generated through a Monte-Carlo approach by mixing recorded noise segments (left) with a source signal waveform, which was propagated from near the source to a particular distance of the detector. The simulated test datasets are then run through various click detection algorithm to assess the detection probability and potential biases due to different propagation assumptions.
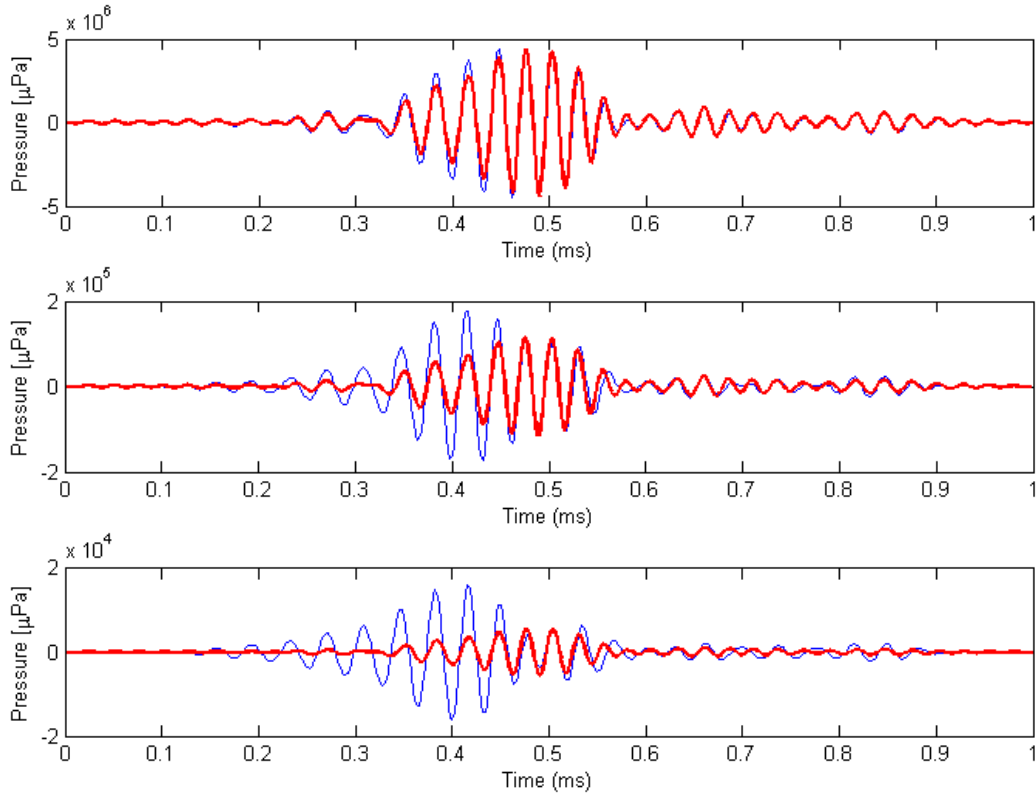
Figure 2. Example of a beaked whale pressure waveform propagated to different range using broadband assumption for frequency dependent absorption loss (blue) and for the narrowband assumption (red) assuming a central frequency of fc = 38000 Hz, and at different source range (top to bottom: 1000, 2000 and 3000 m).

The detectors were applied to sections containing only noise, which allowed us to quantify the false alarm probability for the background noise considered. Combining the probabilities of detection and false alarm provided the receiver operating characteristics needed to assess the performance of a click-detecting PAM system. Use of recorded noise in a bandwidth of relevance to the echolocation click ensured a realistic assessment of the false alarm rate (FAR).

The detection function was then estimated for each species, detector and narrow/broad-band combination by fitting a binary Generalized Additive Model (GAM) to the detection data (number of inserted clicks that were detected by the detector). To ensure the fitted function was monotonic non-increasing, a constrained B-spline basis function was used (Pya and Wood, 2015). The fitted detection functions were used to estimate the relative bias in effective detection range and effective detection area, and the corresponding relative bias in density estimate that can be expected due to narrowband approximation of the propagation loss.

Data simulations were caried out for Blainville's beaked whales (*Mesoplodon densirostris*), known to be sensitive to sonar sound and therefore of high relevance to the US Navy, and sperm whale (*Physeter macrocephalus*) clicks, whose high source level assures long range detection and amplifies broadband effects. Source click waveforms used in this study were obtained from von Benda-Beckmann et al. (2010) for the beaked whale, and Zimmer (2011) for the sperm whale.

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For background noise we used measurements obtained with the Delphinus towed array at the US Atlantic Undersea Test and Evaluation Center (AUTEC), where both Blainville's beaked whales and sperm whales are commonly present. Analysis of the noise levels on the system indicated that the background noise was system-noise limited (von Benda-Beckmann et al. 2010). A three hour segment, previously audited by human operators to ensure no marine mammals were present in during the time of recording, was selected. The Navy acoustic monitoring system provided an independent check to ensure absence of animals near the array (Ward et al. 2008; von Benda-Beckmann et al. 2010).

WORK COMPLETED

Progress to date includes:

- Two click detectors were implemented (a sub-band energy detector, and power law Page test) and applied to towed array data recorded at the AUTEC range (see von Benda-Beckmann et al. 2010).

- False-alarm probabilities and detection probabilities for different detector settings were determined using recorded background noise.

- For realistic false-alarm rates, modelled detection probabilities for beaked whales and sperm whales were determined, for the two detectors.

- Detection probabilities were fitted using statistical detection functions, in order to measure the effective detection range for density estimation.

- Detection functions were estimated using different assumptions for broadband propagation to assess the potential bias in density estimates due to narrowband approximations.

- The findings were used to determine realistic figures of merit (FOM) to extrapolate the potential bias to other odontocete species, using the methods described in Ainslie (2013).

- Intermediate results were presented at the DCLDE2015 workshop in San Diego

- An advanced draft mansucript has been prepared to be submitted to a peer-reviewed journal in November 2015.

RESULTS

To establish meaningful detector settings for the modeled detection functions, two different detectors (a sub-band energy and a power-law Page test) were applied to simulated data of beaked whale clicks and sperm whale clicks in order to determine the false-alarm rate (FAR) (Figure 3). The detection threshold that corresponds to a similar false-alarm probability depended on the species and background noise statistics considered (Figure 3). A low false-alarm rate of FAR=1/h was achieved for detection thresholds between 10 dB and 24 dB. For a high FAR =200/h, detection thresholds ranged between 1 dB and 12 dB. The cross-over between the two detectors for beaked whale clicks, showed that the false-alarm rate was strongly detector dependent.

The detector settings for a low FAR (1/h) and high FAR (200/h) were considered to determine the effective detection radius, and effective detection area to assess the relative bias due to narrowband assumptions in the propagation loss modeling compared to the broadband model (Figure 4).
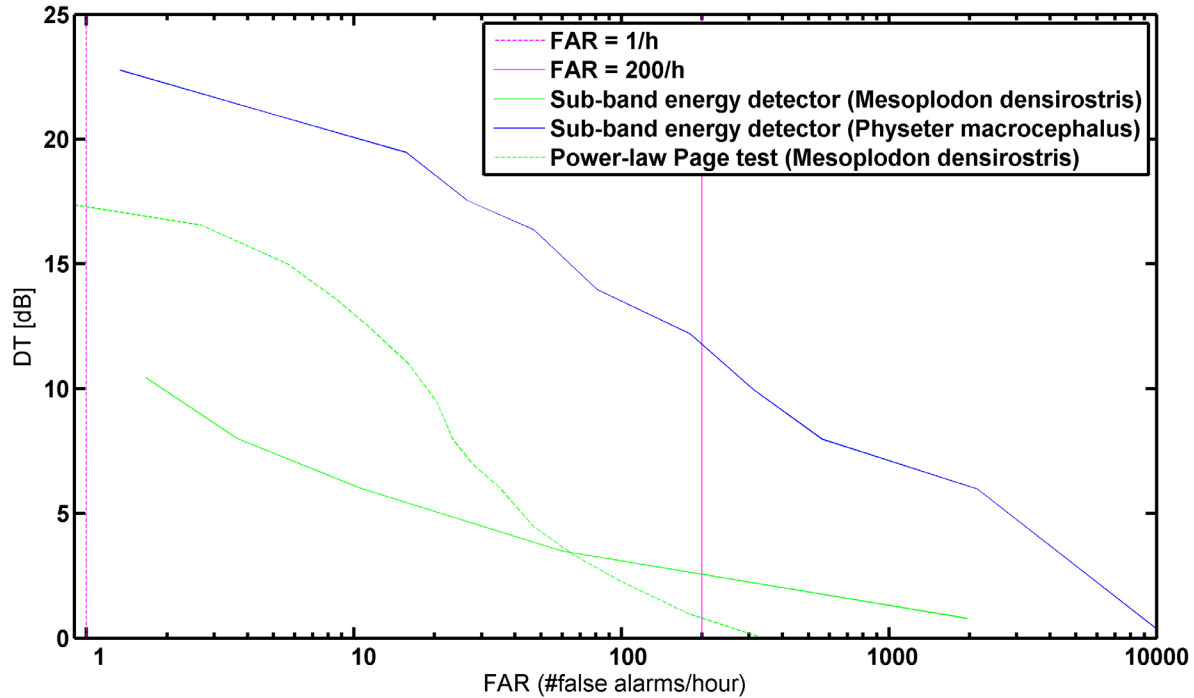
Figure. 3. Detection threshold (DT) vs false-alarm rate (FAR), obtained by varying the detector thresholds, for detection of Blainville's beaked whale (Mesoplodon densirostris) and sperm whales (Physter macrocephalus) echolocation clicks. The colors indicate different detectors used (dashed, energy sub-band detector; solid: power law Page test detector). The dashed and solid magenta lines indicate false-alarm-rates (FAR) of 1/h resp. 200/h. The detection function for a FAR = 1/h and 200/h are indicated by the magenta lines. Notice that a wide range of FAR can be obtained for a given DT, depending on the type of detector used, and species considered.

For the combination of background noise, and detector settings used in the sub-band energy detector, effective detection ranges were predicted of 1.1 – 1.8 km (broadband), and 1.0 – 1.6 m (narrowband) (7 - 10% error) for the beaked whales, with maximum detection ranges up to 2.3 km. The resulting detection function for sperm whales showed a much larger difference between the two methods, with effective detection distance of 6.5 – 13.8 (broadband) and 4.9 – 8.9 km (narrowband), and a larger relative bias of the NB relative to the BB approximation (25 – 35 %). The bias in predicted effective detection area resulted in 11 – 21% for Blainville's beaked whales, and 76 – 138% for sperm whales.

The sub-band energy detector and the power-law Page test detector predicted somewhat different effective detection ranges for a similar FAR. For a low FAR (high detection threshold), the broadband effective detection range predicted with the power-law Page test detector was somewhat smaller than for the sub-band energy detector (0.84 vs. 1.03 km), whereas at high FAR (low detection threshold), the power-law Page test predicted slightly higher broadband effective detection ranges (1.86 vs 1.80 km).
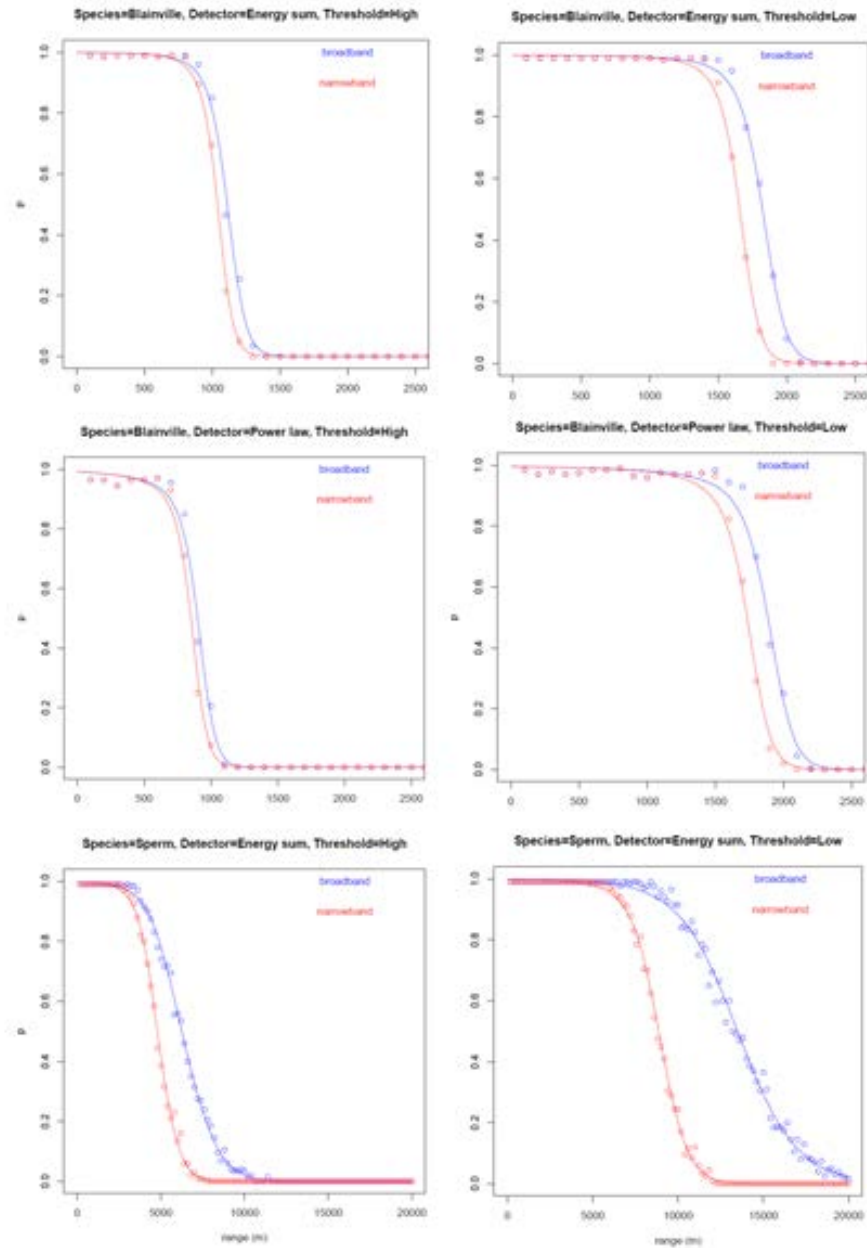
Figure 4. Detection functions of simulated echolocation clicks added to background noise for different species and detectors. Circles indicate probabilities of detections obtained by modeling the propagation loss using a broadband approximation (blue), and narrowband approximation (red). Solid lines indicate fits of detection functions, used to measure the effective detection ranges and areas. Top: Detection function of a single on-axis Mesoplodon densirostris (Blainville's beaked whale) click using a simple energy detector (with DT=7 dB) corresponding to a FAR = 10/h, and DT = 3 dB, corresponding to a FAR ~ 200/h). Middle: Detection of a Blainville's beaked whale click using a power law Page test detector (with DT = 12 dB) corresponding to a FAR = 1/h, and DT = 2 dB, corresponding to a FAR ~ 200/h). Bottom: Detection function of a single on-axis Physeter macrocephalus (sperm whale) click using a simple energy detector (with DT = 23 dB, corresponding to a FAR = 1/h, and with DT = 11 dB, corresponding to a FAR = 200/h). Note that variance estimates were omitted. A system-noise limited background noise was adopted for this example (see von Benda-Beckmann et al. 2010).

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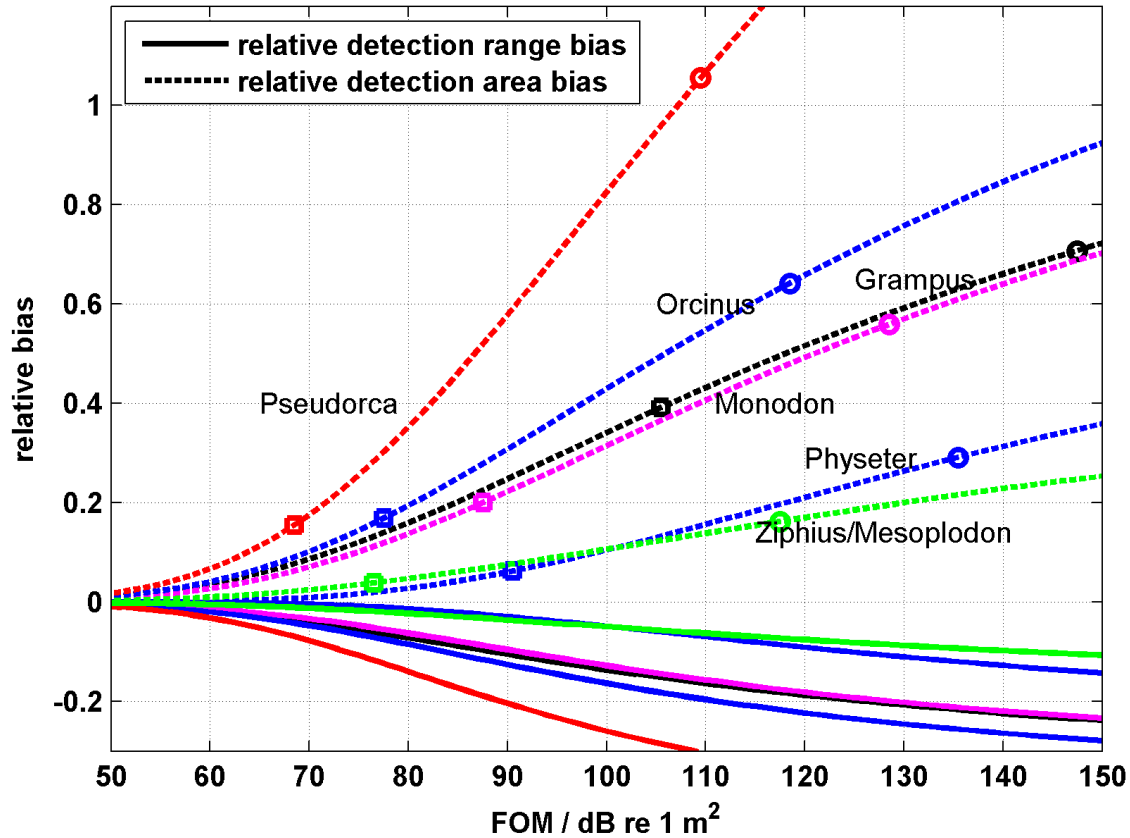

Figure 5. Modeled relative bias in detection range (solid lines), and detection area (dashed lines) for different Figure-Of-Merit (FOM), with the typical FOM for scenarios considered in this study. These scenarios considered a system-noise limited case with high detection threshold (DT =20 dB, indicated by the squares), and circles indicate the detection performance when the system is detecting in ambient noise limited conditions, for a sea state of SS=2 (Wenz, 1962) using a low detection threshold (DT=5 dB).

For the beaked whale case the predicted density bias by the passive sonar equation was a factor 2 lower than the estimates obtained from the more detailed computation of the detection function derived in this study (Figure 5). The detection function for the low detection threshold from this study was in agreement with the detection function previously predicted by von Benda-Beckmann et al. (2010), for comparable source level and detector settings considered in that study. However, the bias may be larger when ambient noise conditions are considered (see Figure 5).

For the sperm whale, the passive sonar equation predictions were much smaller than those obtained with the detailed model (5-10 % compared to 76-137%). The mismatch between these two approaches had two reasons: 1) The source click waveform adopted here had somewhat lower frequency content than assumed in Ainslie (2013). This was probably a result of propagation effects that had cut off the higher frequency content of the recorder click. Because the energy source level was assumed to be the same for both approaches (simulated data and passive sonar equation), the lower frequencies had higher spectral energy levels, leading to larger propagation distances, and thus a larger estimated bias. 2) Ainslie (2013) considered top-hat approximation of the click spectrum, with width equal to the equivalent bandwidth. After propagation to distance, the sperm whale click presented here had its dominant energy content below the frequency band considered by Ainslie (2013). Because of its lower frequency, this click was less attenuated and therefore detectable to larger distances, thus also increasing the detection range and the resulting bias of the density estimate. In order to disentangle the two effects, the source waveform in Figure 1 needs to be back-propagated to obtain a source click spectrum of sperm whales in better agreement with those reported in the literature (e.g. in Møhl et al., 2003).

It was concluded that the bias introduced by making narrowband assumptions in the propagation loss depended on the species considered, and type of detector and detector settings used, but ranged typically between 5 % to more than 100% for some species (Figure 5). Our results showed that one should be cautious about assumptions made on the bandwidth of the echolocating click when using the passive sonar equation. The low frequency content of an echolocation click can become important for modeling the detectability at larger distances, even though the dominant energy contribution in the source click spectrum transmitted by the animal occurs at higher frequencies, When neglected, this may lead to an underestimate of the actual detection distances that can be achieved for the type of detectors considered in this study.

IMPACT/APPLICATIONS

Estimates for the abundance of marine mammals are required for the assessment and effective mitigation of the impact of naval activities, such as sonar or underwater detonations, on marine mammals. Obtaining reliable and unbiased abundance estimations of marine mammals is essential, because in environmental impact assessments a bias would cause an under- or over-estimate of the number of marine mammals affected by naval activities.

The study resulted in guidance on the species and conditions for which a simplified use of the passive sonar equation can be used to obtain unbiased population density estimation, or for which more elaborate and time-consuming modeling of the click propagation and detection is required. Such guidelines can then be used for ongoing and future PAM projects that rely on detection of broadband echolocation clicks.

The method developed in this study improves the accuracy of marine mammal density estimation based on counting echolocation clicks, and will be applicable to density estimates obtained using different PAM-approaches, including bottom-mounted/ deployed hydrophones and line transect surveys.

RELATED PROJECTS

Effect of broadband nature of marine mammal echolocation clicks on click-based population density estimates (grant number: N000141410409, PI: Michael Ainslie, TNO).

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